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INVESTIGATION OF CLUSTER STATES IN ^{13}B USING THE ^{9}Li–α RESONANT ELASTIC SCATTERING*

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The excitation function of the resonant reaction ^{4}He(^{9}Li,α) was measured with the aim of investigating the compound nucleus ^{13}B. These measurements were performed in inverse kinematics at center-of-mass scattering angles close to 180° by using a thick ^{4}He gas target and a ^{9}Li beam. The ^{13}B excitation energy region explored was 14–20 MeV where ^{9}Li–α configurations of ^{13}B are predicted by Antysimmetrised Molecular Dynamics calculations. The measured excitation function at $\theta_{\rm cm} = 180°$ shows different clear structures in a ^{13}B excitation energy region which was experimentally unknown.

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1. Introduction

Clustering phenomena are well-known in nuclear physics. Indeed, some properties of nuclei can be simply described by assuming a nuclear structure made of a few weakly interacting clusters. Generally, the nuclear cluster is a strongly bound system, typically an α particle. In fact, first evidences of nuclear clustering concerned nuclei which have even, and equal, numbers

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of protons and neutrons (α-conjugate nuclei). It is known that the cluster structure is absent in most ground states and that cluster states are to be found at an excitation energy near the separation energy of the clusters (threshold rule). Also non-alpha-conjugate nuclei may present a cluster structure. In n-rich nuclei, the α–α cluster structure as a core may persist, however, it is the exchange of neutrons between the α-particle cores which binds the system [1].

Light exotic nuclei may show a different cluster configuration where the clusters may not only be ordinary stable particles, as for example the α particle, but also somewhat deformed and easy to polarize. This is the so-called exotic clustering that was claimed to become more and more favored when nuclei approach the drip line [2]. Hence, in light unstable nuclei, one of the questions to be answered is how does the cluster structure change with the increase of the neutron number. As far as experimental observations of exotic clustering are concerned, the literature is not so rich, mainly due to the difficulty of performing experiments with the typically low currents of radioactive beams, very often needed for this type of researches. One of the experimentally most studied system is the ^{12}Be nucleus for which very different conclusions on the existence of a rotational band associated with an exotic ^{6}He–^{6}He cluster configuration have been drawn [3–5]. As far as boron is concerned, calculations performed in the framework of Antisymmetrized Molecular Dynamics (AMD) [6] describe some of the states of the very neutron-rich isotopes in terms of two clusters of He–Li type. The ground state of ^{13}B shows mainly single particle characteristics due to the $N = 8$ neutron shell closure, nevertheless He–Li cluster configurations of its excited states are predicted by AMD and are to be searched for in the excitation energy region close to, or larger than, the decay threshold of the nucleus into the two components under consideration. The ^{13}B decay threshold into ^{4}He+^{9}Li is around 11 MeV. AMD calculations, performed by Kanada-En'yo *et al.* [7], show the presence of a $K^{\pi} = 1/2^{-}$ band having a ^{9}Li–α cluster structure with a band head around 10–13 MeV and excitation energies up to about 20 MeV [7]. An incredibly large deformation, larger than superdeformation, arises in the $K^{\pi} = 1/2^{+}$ band ($\beta = 0.74$). A mixing of both, the largely deformed configuration mentioned above and the ^{9}Li–α cluster configuration constitute the rotational band $K^{\pi} = 1/2^{+}$ with a prominent ^{9}Li–α structure for the higher spin states $7/2^{+}_{3}$ and $11/2^{+}_{1}$. Unfortunately, the ^{13}B excitation energy region where these states are predicted is totally unknown experimentally. Therefore, in order to investigate the existence of ^{9}Li–α structures in ^{13}B, we studied the excitation function for the ^{4}He(^{9}Li,α) elastic scattering process. In the following, the experiment ^{9}Li+^{4}He at $E_{\rm lab} = 32$ MeV will be discussed and results of the ^{13}B excitation function in the region of 14 MeV$\leq E_{\rm x} \leq 20$ MeV will be shown.

2. Experimental set-up and data analysis

For this experiment, the Inverse Kinematic Thick Target method was used. The experiment was performed at TRIUMF (Canada) using the ^{9}Li beam at 32 MeV delivered by the ISACII facility. The target consisted of the TUDA chamber filled with an isotopically pure ^{4}He gas at pressures of 650 and 680 Torr. The chamber was separated from the high vacuum beam line by a Kapton window ≈ 12 μm thick. Elastically scattered α particles were detected and discriminated from other reaction processes using both ΔE–E and Time-of-Flight (ToF) techniques. The detection system consisted of three telescopes each made of a four quadrants, 50×50 mm^{2}, 50 μm thick Si as ΔE detector and a 50×50 mm^{2}, 1000 μm thick Si as residual energy detector. One of the telescopes was placed around 0° and a second one next to it downstream the TUDA chamber. The gas pressure, in fact, was enough to stop the beam before it reached the detector but not the recoiling α particles. A third telescope was placed closer to the entrance Kapton window, at about half the distance from the window of the other two telescopes, as sketched in Fig. 1. In this way, although the full excitation function was not measured by this telescope, being placed at larger angles than the other two, some information on the angular distribution for the highest energy events (the ones occurring near the entrance window) could be gathered.

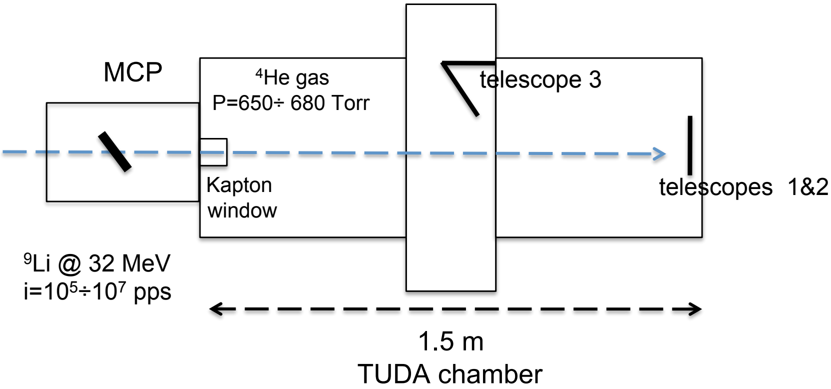

Fig. 1. Sketch of the experimental set-up.

A microchannel plate (MCP) detector was placed under vacuum, just upstream the entrance window, in order to give a signal whenever a ^{9}Li beam particle entered into the chamber. The MCP gives a way to count the beam particles, necessary for the cross-section normalization and, at the same time, provides a time signal for the ToF measurement. The beam intensity when using the MCP detector was kept to $\simeq 5 \times 10^{5}$ pps. In the last runs of the experiment, the MCP detector was switched-off and the beam intensity was increased to 10^7 pps. These runs were normalized to the low intensity runs where the MCP detector was on.

The detectors around 0° were detecting also the βs and the β-delayed αs coming from the radioactive decay of the ^{9}Li beam. In Fig. 2, it is shown the ΔE *versus* ToF 2D-spectrum; in this spectrum, a large background can be seen. Due to the background, the events of interest could be selected with a c.m. energy threshold of ~ 4 MeV. The detection threshold creates the two bands of ToF uncorrelated events originating from the radioactive decay of the beam observed in Fig. 2. In Fig. 3, it is shown the ΔE *versus* E 2D-plot for one of the detectors placed at 0°. In this figure, it is possible to see β background; although the detector thicknesses is rather small, large angle scattered β particles can deposit large energies in the Si detectors.

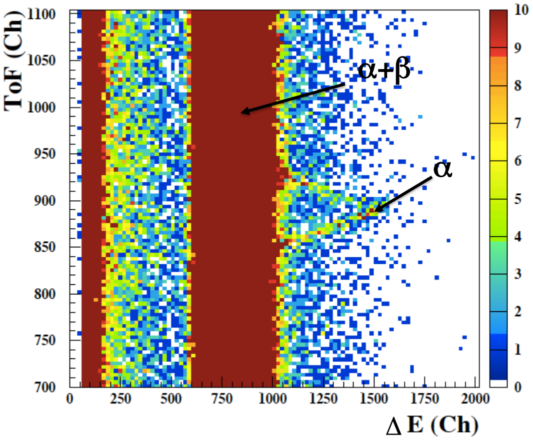

Fig. 2. Time of Flight *versus* ΔE energy 2D spectrum for a detector placed at 0°. The ToF corresponds to the sum of the Time of Flight of the beam before interacting with the target plus the Time of Flight of the recoiling α particles. Background events, uncorrelated in time, coming from the ^{9}Li radioactive decay can be observed.

Events of interest were selected by putting gates in the ΔE *versus* ToF spectrum for the events stopping in the ΔE detectors, with the condition that no events on the E detector were present; whereas, for the high-energy events, punching through the ΔE, gates on both ΔE *versus* ToF and ΔE *versus* E were put. Background subtraction was performed by shifting the gates in the ΔE *versus* ToF in a different time region.

Center-of-mass energy spectra were obtained from the energy deposited in the detectors and the angles of the recoiling α particles. In the case of the elastic scattering process, energy and angles of the recoiling particles are

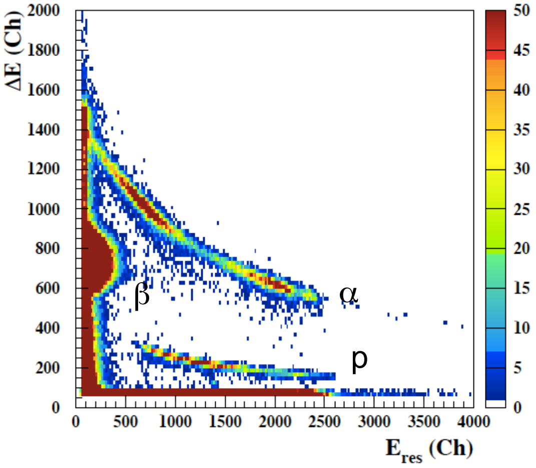

Fig. 3. ΔE *versus* E_{res} 2D-spectrum. Alpha particles, protons and background beta particles are observed.

uniquely related to the position in the target at which the scattering process occurs, via kinematics and energy loss calculations of the beam and recoiling particles. For the events punching through the ΔE detectors, the total energy ($\Delta E + E_{\mathrm{res}}$) was reconstructed on an event-by-event basis correcting also for the energy loss in the dead-layers of the detectors and in the gas in between the two detectors of the telescope. The excitation energy spectrum of ^{13}B was obtained from the E_{cm} spectrum by adding the two-body Q_{val} and it is shown in Fig. 4.

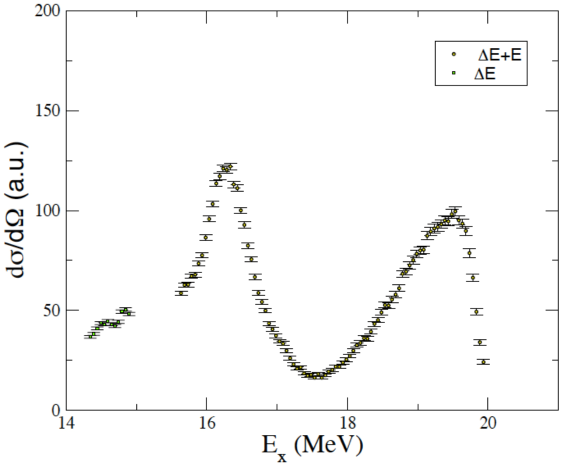

Fig. 4. Preliminary ^{13}B excitation energy spectrum at $\theta_{\mathrm{cm}} \sim 180°$.

In Fig. 4, it is possible to observe at least two large peaks at excitation energies of ~ 16.3 and 19.5 MeV. The peak at 19.5 MeV is very asymmetric — an indication that it could originate from the superposition of more states. Information gathered on the other detectors, placed at different angles, indicates that at least three peaks are contributing to this large structure observed. These results are still under analysis.

A thorough theoretical analysis of the full experimental data is required to establish if the nature of the observed peaks in the ^{13}B excitation function are of ^{9}Li–α type as predicted by AMD calculations [7].

3. Conclusions

The existence of exotic clustering in odd-boron isotopes of He–Li type has been predicted by AMD calculations [6]. In the case of the $N = 8$ neutron-closed-shell ^{13}B nucleus, ^{9}Li–^{4}He cluster configurations are predicted at excitation energies above the break-up threshold of ^{13}B into ^{9}Li–^{4}He that is 10.8 MeV. In this work, details of the Resonant Elastic Scattering ^{4}He(^{9}Li,α) experiment performed at TRIUMF laboratory have been discussed. The ^{13}B excitation function measured at $\theta_{\rm cm} \sim 180°$ in the range of 14–20 MeV shows indeed two large structures which are likely to be due to more than two states. The extraction of the excitation function at all angles, and the following theoretical analysis, will allow to understand whether the observed structure can be associated to the predicted exotic cluster states of ^{13}B.

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